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# Spacecraft Observatory Benchmark Problem for Optical Disturbance Rejection

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# *Outline*

- Background
- Space Missions with Optical Payloads
- Survey on Disturbance Rejection Methods
- Proposed Benchmark Problem
- Summary
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# *Background*

NASA GN&C Technical Fellow (Neil J. Dennehy) proposed to create a benchmark spacecraft to study the Observatory (Space Telescope) type of application.

A Benchmark Problem to explore the following:

- Line of Sight (LOS) payload stringent pointing stability requirement
- LOS payload Controls Structures Interaction (CSI)
- Variable mass properties and flex-body dynamics variations
- Aggressive payload steering agility
- Adaptive attitude controller/filter for payload LOS disturbance rejection
- ConOps observational requirements

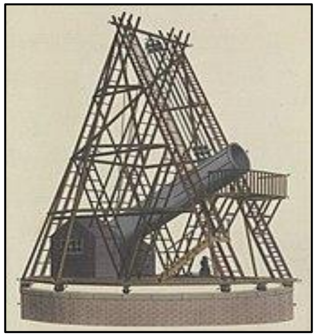
# *Brief History of Spacecraft with Optical Payload -- Its Challenges and Solutions*

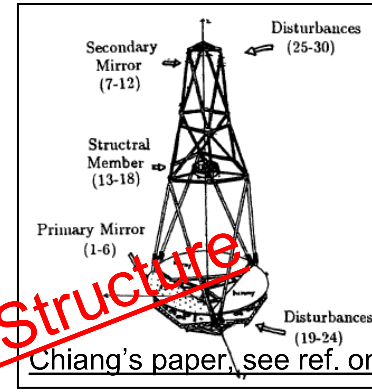
## *Gen I: Control-Structure Interaction*
## *Gen II: Optical Payload Disturbance Rejection*

# Gen I: Optical Payload on Large Space Structure (LSS)

William Herschel - Wikipedia

*1789 Herschel's*
*12 m Telescope*
*1800 discovered*
*Infrared Radiation*



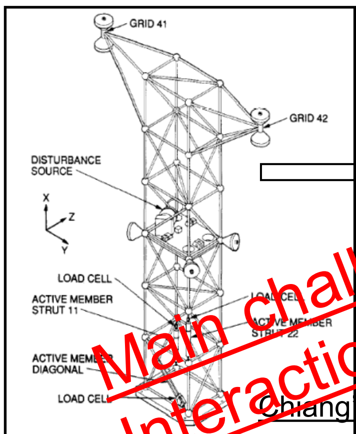




Chiang's paper, see ref. on p.40

*JOSE*
*1986*

*JPL CSI program*

*JPL CSI testbeds in 90's*




Chiang's paper, see ref. on p.41

Phase B Testbed → Phase C Testbed →

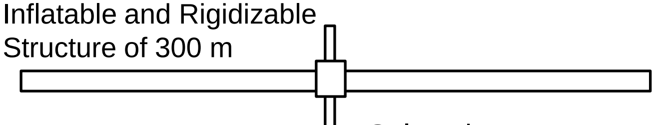
Main challenges: How to surppress Control-Structure Interaction for precise payload LOS pointing..

*JPL SIM mission*


*Hubble*
*1997-2009*

*James Webb Space Telescope 2021*

Inflatable and Rigidizable Structure of 300 m



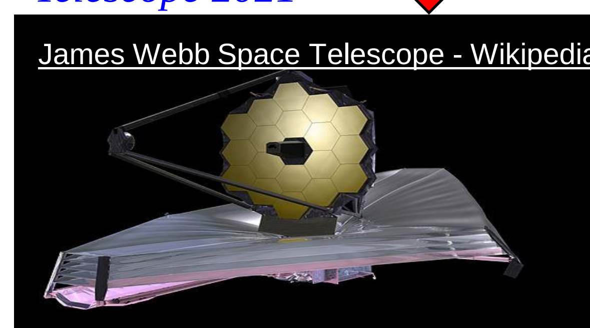
Solar wings

*DARPA*

*ISAT 2005, Paper Study*

Chiang, et. al, AIAA GNC Conf. 2008

Hubble Space Telescope - Wikipedia

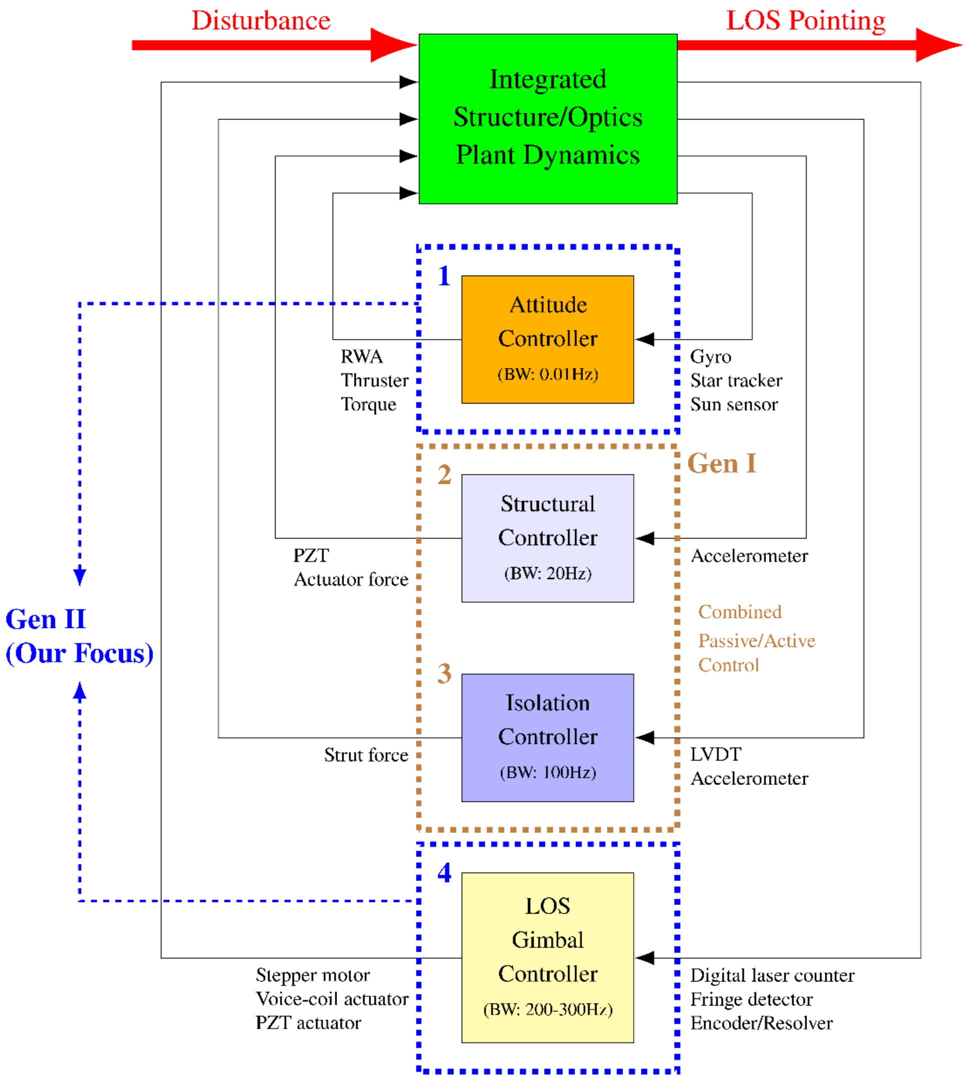


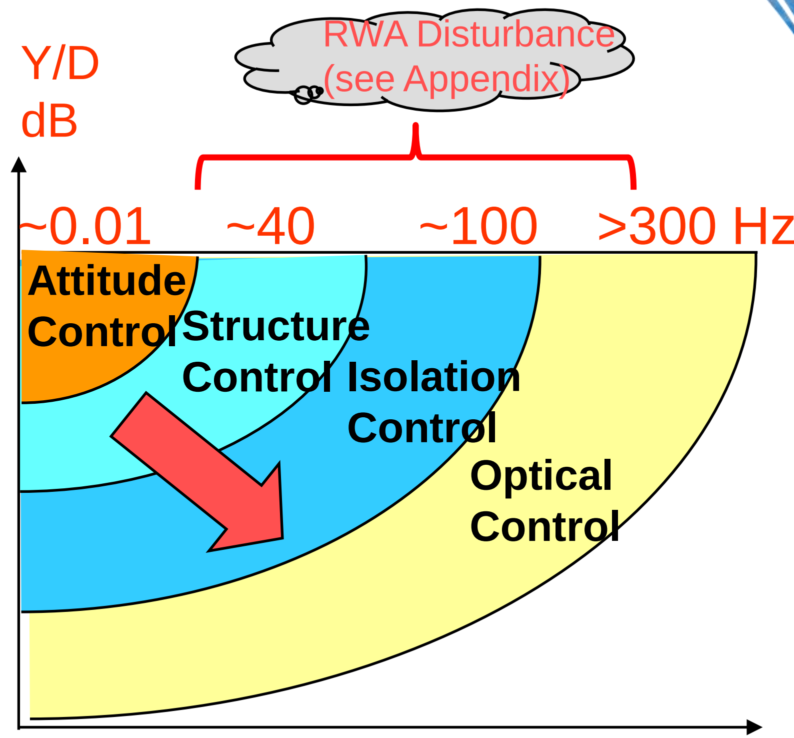
# Gen I: Control Structure Interaction (CSI) Problems

- CSI problems have occurred in every stage of space system life cycles with impact ranging from moderate to very serious

- 1958 – 1990, numerous CSI problems happened
  - Unstable spin, saturated gyro, rapid spin decay, unstable roll, depleted fuel, transfer orbit instability
  - Excessive vibration, excessive oscillations in attitude, solar array and controller interacted, flutter of boom antenna, and nonrepeatable modal frequencies for identical parts
  - Any redesign control law adding design cost/schedule impact

# Multi-layer Active Optical/Structure Control System



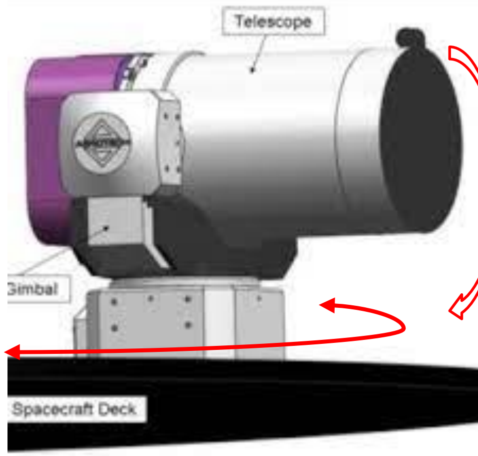

*Sensitivity Reduction*
*Disturbance Rejection*
*(with all layers: 5100:1)*

***Gen I: 90's~2010 Focus: layer 2 & 3 -- Control Structure Interaction (CSI)***
***Gen II: 2010+ Focus: layer 1 & 4 -- Optics Disturbance Rejection (ODR)***

# Gen II: Spacecraft with Optical Payloads (No LSS)

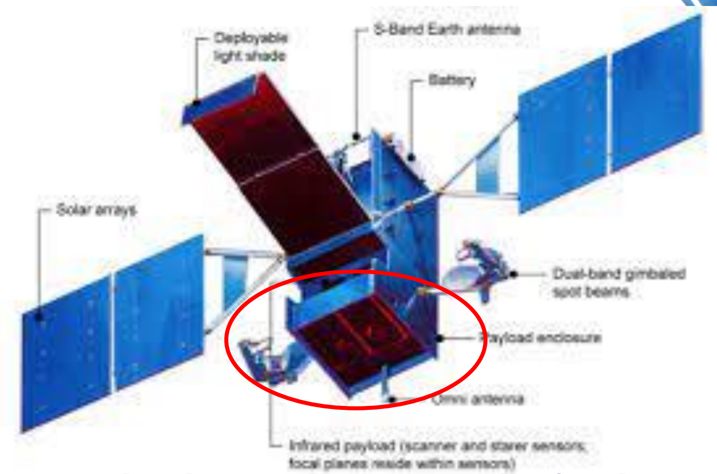
## DSP (1960's-2007)

## Telescope




Defense Support Program - Wikipedia

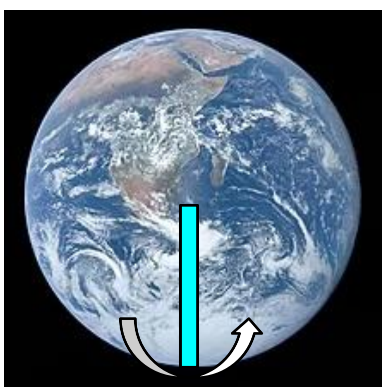
## Scanner/Starer Mirrors




http://en.wikipedia.org/wiki/Space-Based_Infrared_System

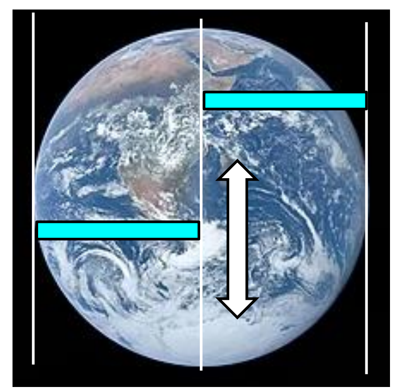
## Different Scanning Patterns:

DSP Circular Scan



*Earth - Wikipedia*

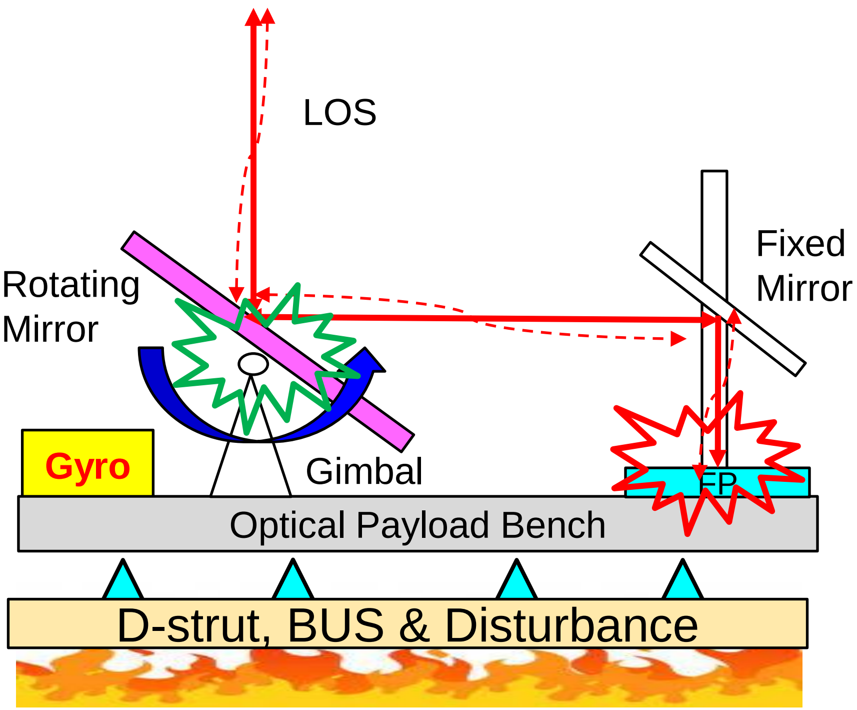
SBIRS Linear Scan



*Earth - Wikipedia*

***Main challenges: Reject optical payload internal/external disturbances and keep its LOS pointing up to "urad" level in wide frequency range.***

# *Knowing your "Plant" well is the key to Control it.. -- LOS in Optomechanical Systems*




Main LOS Jitter Sources:
1). Focal Plane Vibration ,
2). Mirror Servo Vibration "residuals"

**Passive D-Strut:** helps rejecting disturbances on mechanical structure such as "Focal Plane", "Mirror Assembly"

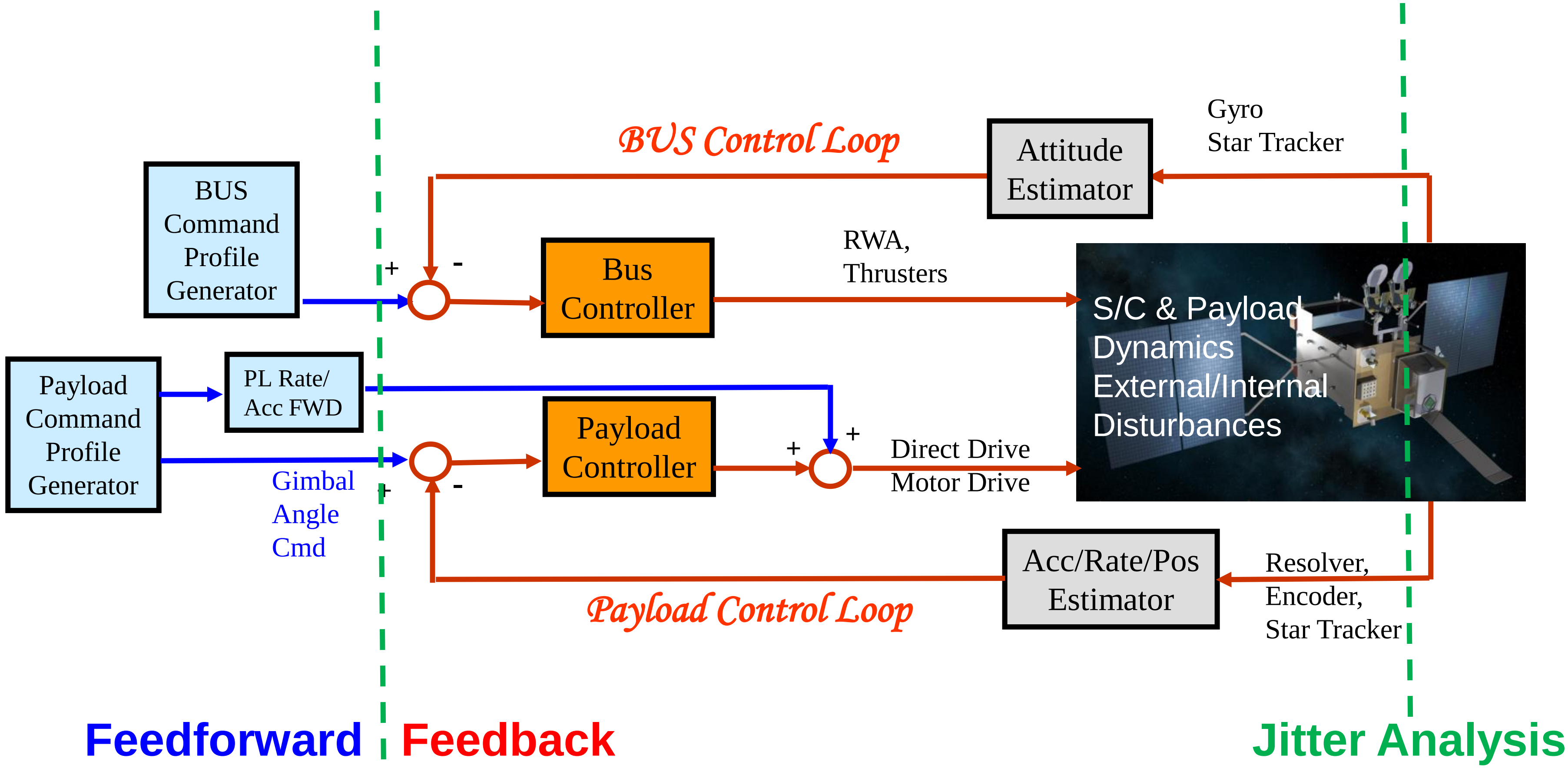
**Active Gyro:** 1). Propagating inertia attitude, 2) Sense both internal and external disturbances and feed forward to mirror control loops to cancel them.

***The question is: "how much" and "how wide in frequency range" can the disturbances can be rejected ?!***

# Payload/Spacecraft Control Block Diagram

<u>Basic Control Design Strategy:</u>

- Feedback (stability, disturbance rejection, BW, pointing accuracy)
- Feedforward command (decouple BUS/Payload motion, <u>additional</u> rejection against external/internal disturbances)
- Jitter Analysis



# *Summary on Optical Payload on LSS/Spacecraft*

Gen I - Well Established CSI Problem

| | | Benchmark Problem | Layer 1 (BUS Control) | Layer 2 (Structure Control) | Layer 3 (Isolation Control) | Layer4 (LOS Control) | Notes |
|---|---|---|---|---|---|---|---|
| Gen I (CSI) | 1 | **Jose (1985-1988)** | | Collocated Rate Feedback | | H-infinity | * Large space structure<br>* Study of structure/LOS control |
| | 2 | **CSI Phase A (1991-1993)** | | Non-Collocated H-infinity | | | * Large space structure<br>* Study of structure control |
| | 3 | **CSI Phase B (1993-1996)** | | Non-Collocated H-infinity | Passive/Active spring/damper | H-infinity | * Large space structure<br>* Full study of LOS disturbance rejection |
| | 4 | **CSI MPI Testbed (1996-1999)** | | Non-Collocated H-infinity | Passive/Active Spring/Damper | H-infinity | * Large space structure<br>* Full study of LOS disturbance rejection |
| | 5 | **Two-Mass-Spring (1991-1992)** | | Non-Collocated H-infinity | | | * Focus on structural uncertainty/robustness and known periodic disturbance |
| Gen II (ODR) | 6 | **Defense/Science Missions (1970's -present)** | Classical Controller | | Passive Spring/Damper | Classical/ H-infinity Controller | * With gyro feedforward disturbance rejection scheme |
| | 7 | **Spacecraft with Optical Payload (2023 and beyond)** | Classical Controller | | | Gen II Benchmark Problem | * Study of disturbance rejection methodology |

Gen II Benchmark Problem Focus on Layer 4

# *LOS Disturbance Rejection Methods*

**Hardware**
Approach 1: D-strut (single/multi-layers, widely used in industry)

**Software**
Approach 2: Disturbance Estimator Approach

**Hybrid**
Approach 3: Sensor Fusion & H-infinity Filtering (Aerospace IRAD)

# *Summary of Existing Disturbance Rejection Methods*

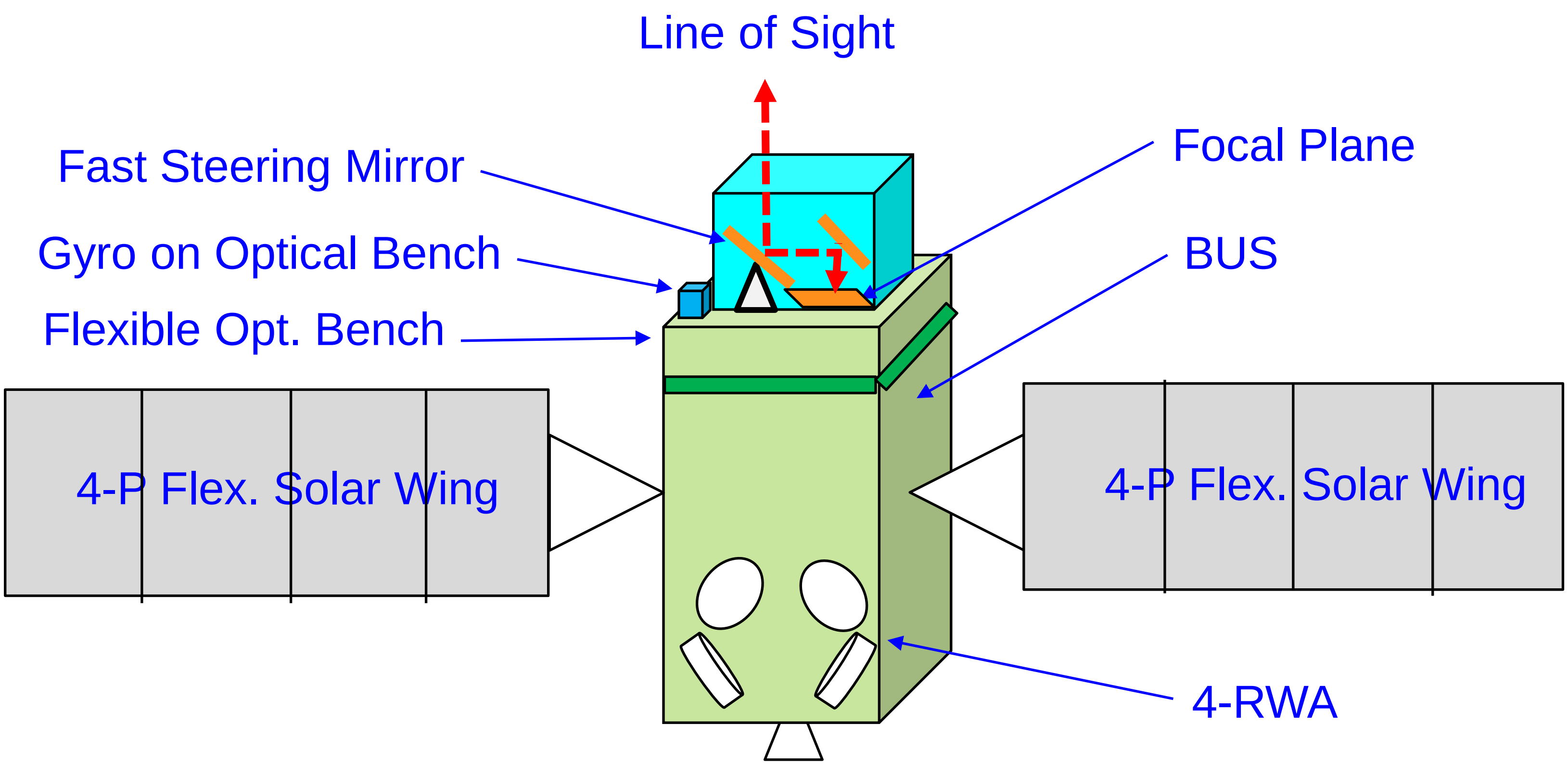
| LOS Disturbance Rejection Methods | Hardware | Software | Potential Rejection Ratio (RMS) | Pros and Cons |
|---|---|---|---|---|
| **1. D-strut -- Hardware** | Passive Damper | | 2 to 1 | **Pros:** easy approach **Cons:** unpredictable mode attenuation, limited by noise floor, additional cost & weight |
| **2. Disturbance Estimator -- Software** | | Digital Filters | 3~5 to 1 | **Pros:** effective in many applications, adaptive to environmental changes **Cons:** needs to work with the original controller for stability |
| **3. Sensor Fusion -- Hybrid** | Gyro + MHD | Digital Filters | **8~10 to 1** | **Pros:** very effective disturbance rejection **Cons:** require advanced filter design for sensor robustness |
| | | | | |

**_Proposed Benchmark Problem on Spacecraft with Optical Payload_**

**_-- Focus on Layers 1 & 4_**

**_"Disturbance Rejection Methodology"_**

# Proposed Benchmark Observatory Spacecraft




**Optical Payload Control Design**

1. A simple rigid-body + flexible wing dynamics is sufficed to study disturbance rejection problem (altogether about 50 states linear model)
2. High BW mirror servo for pointing command tracking performance
3. Servo stability and robustness against in-flight dynamics variations deviated from the nominal design model
4. *Focus on high BW LOS disturbance rejection against a wide range of BUS RWA operations*

# Plant Model – Payload and Bus

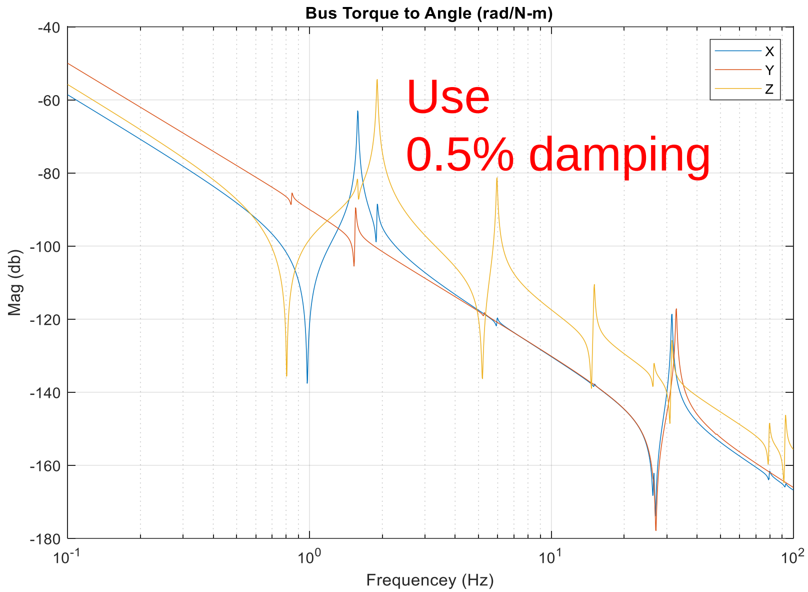
- Payload
  - Rigid bodies: Main Body + Steering Mirror (AZ and EL axes)
  - Spring connections between bus and payload; spring constants selected to mimic internal payload modes (> 40 Hz)
  - Spring connections along AZ/EL axes; spring constants represent flexures (around 2 Hz)
  - Inputs:
    - Torque along AZ/EL axes
    - Cryocooler grid point forces/torques
  - Outputs:
    - Gyro grid point angles
    - Encoder angles about AZ/EL axes
    - Optics grid point displacements/rotations (focal plane, primary mirror, steering mirror) for LOS equation (LOS equation coefficients)

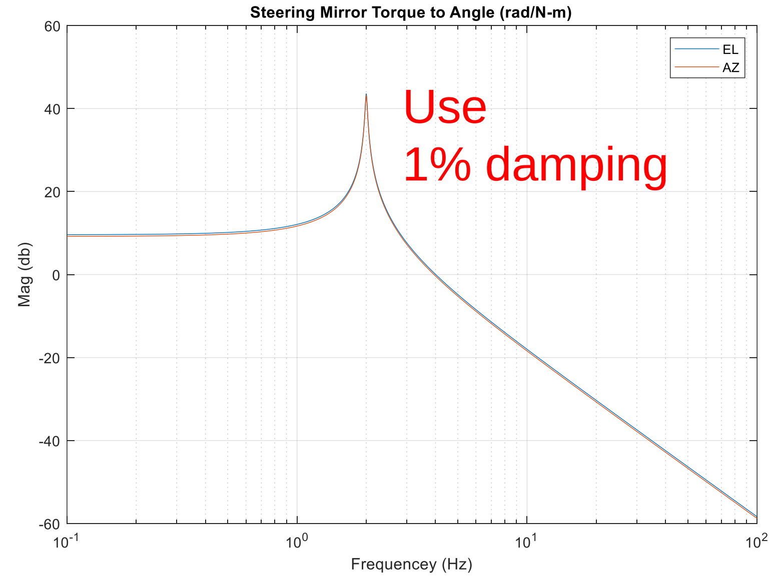
- System
  - Mass properties
- Bus
  - Rigid body
  - Inputs
    - Reaction wheel torques (external torques along 4 wheel axes)
    - Reaction wheel disturbance forces/torques (common grid in Bus-frame)
  - Outputs
    - Star tracker grid point angles
- Solar arrays
  - Rigid panels (4 per solar array)
  - Spring connections between bus and panel, and inter-panel
  - Spring constants selected to get desired mode frequencies (first frequency around 1 Hz)

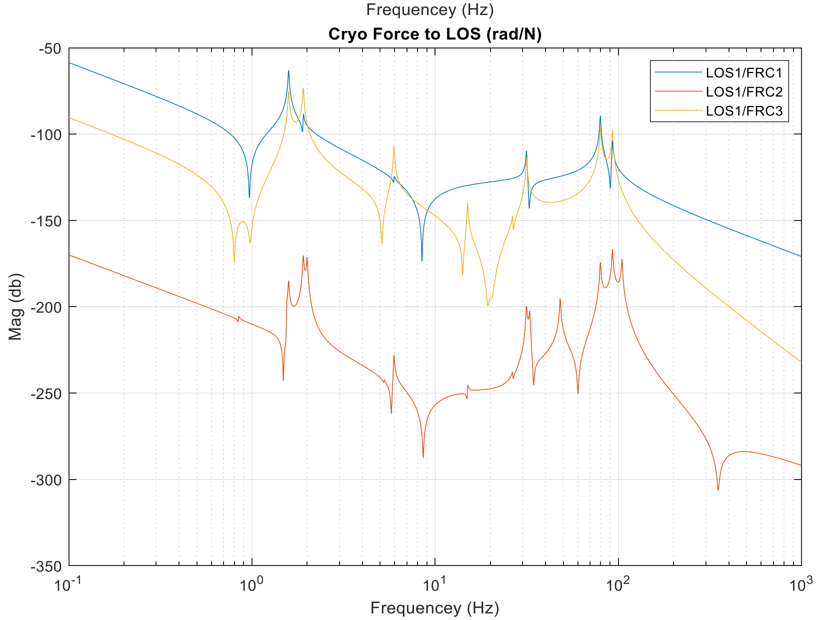
***A 52-state linear state-space model is built from scratch to accomplish the above dynamic characteristics.***

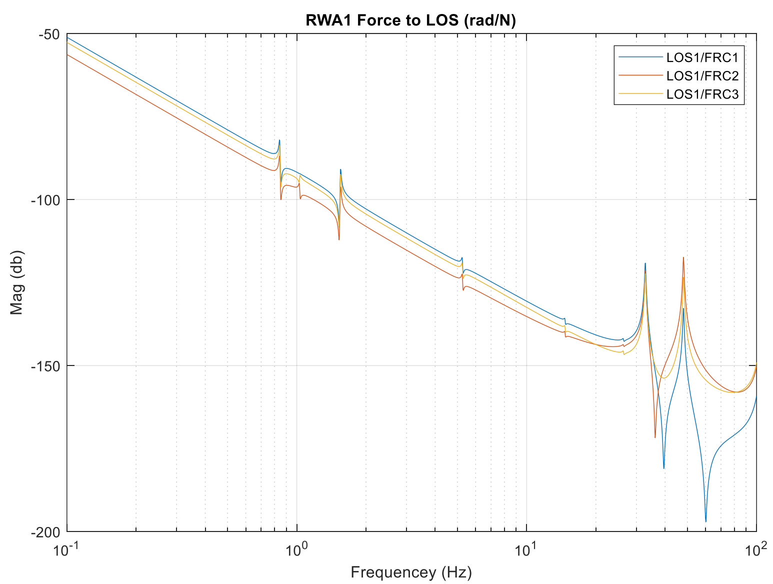
# Iteration #3 Model Responses

*-- 52-state original continuous model*

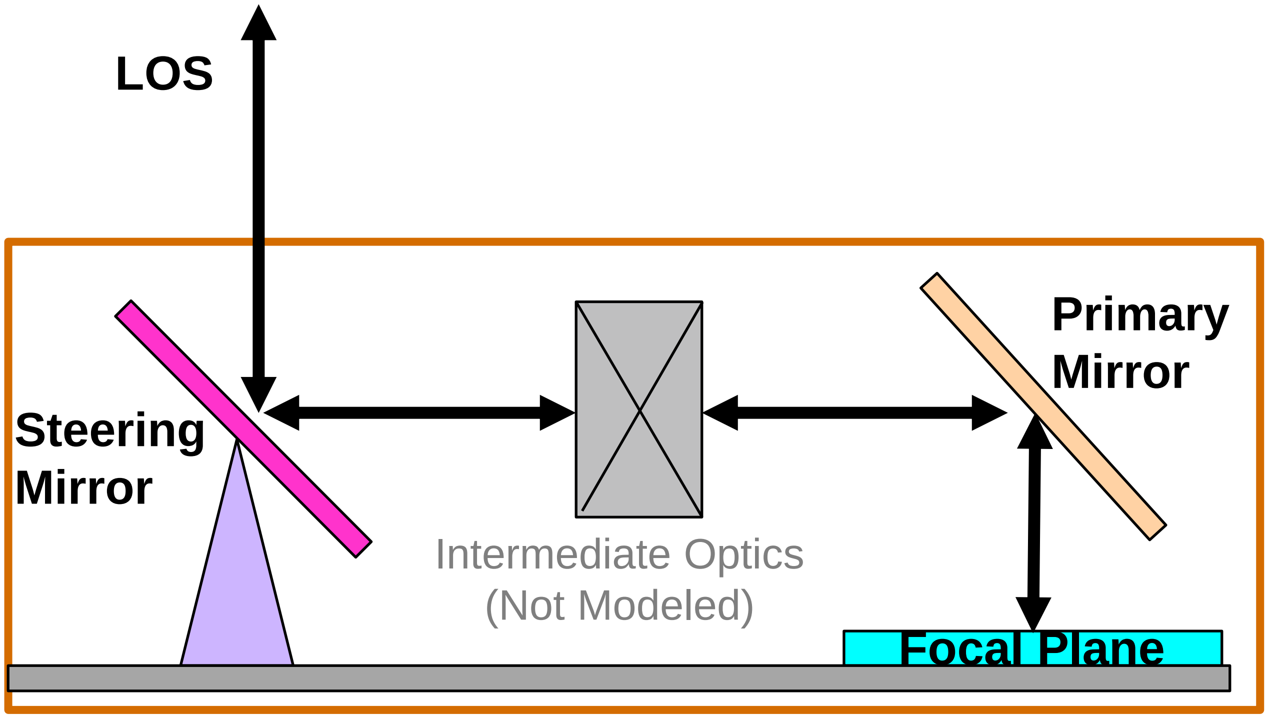


# *LOS Path inside Optical Payload*




$$\hat{s}^{PLD} = \widehat{M}_{\text{Pri}} \cdot \widehat{M}_{\text{Pnt}} \cdot \hat{C}^{PLD}_{ECI} \cdot \vec{r}^{ECI}$$

Primary Mirror Reflection

Steering Mirror Reflection

Get Star Vector In Payload Frame

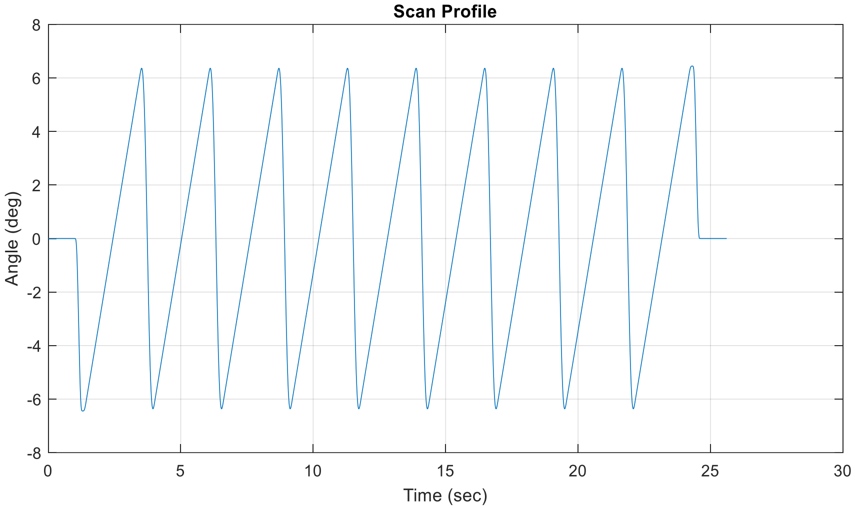
***Linear LOS error mapped from gimbal angle and focal plane will be included in the state-space model as a standard output channel.***

# Payload Command

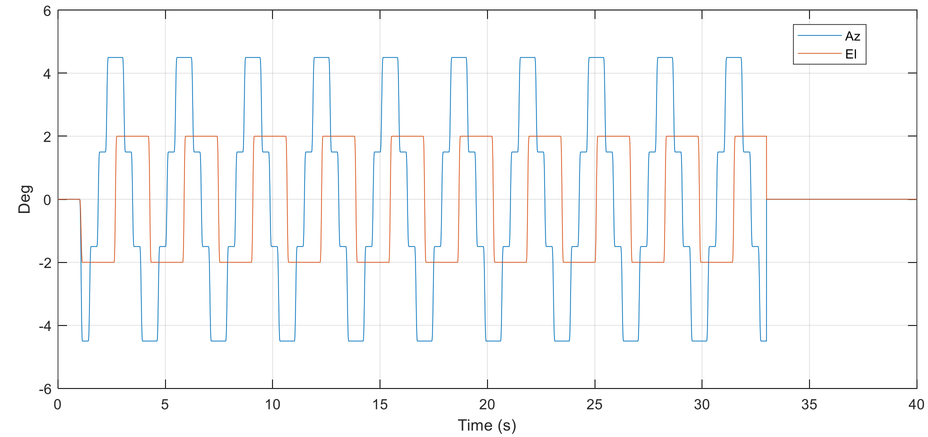
## Descriptions

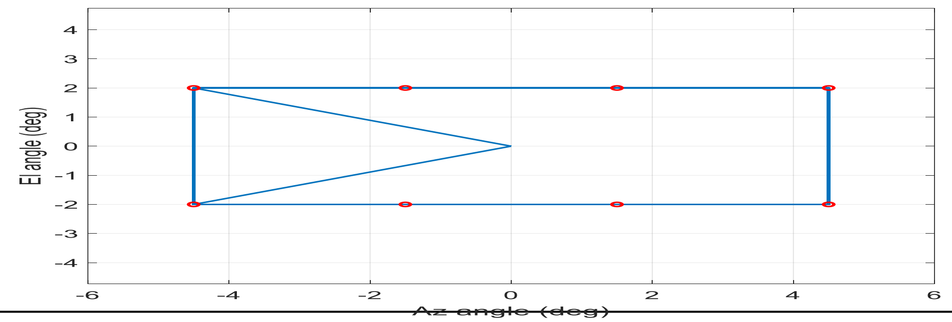
- LOS pointing accuracy is determined under various payload commands
- Depends on the mission applications, there two major types of commands as shown below

Linear Scan




Step-Stare

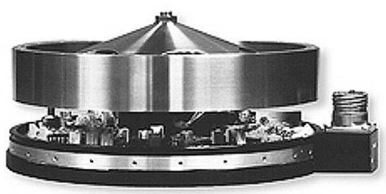


# Payload *External* (BUS RWA) Disturbance

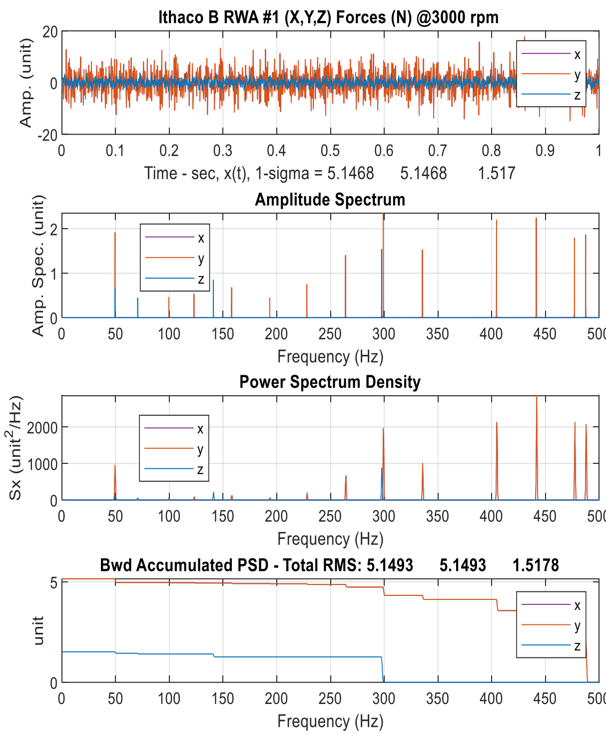
## Descriptions

- BUS RWA motions will impose the largest disturbance to optical payload LOS
- PSD of each wheel force and torque along each wheel axis (X,Y,Z) running at maximum allowable speed will be provided..
- **Commercial Example:** Ithaco B wheel at **3000** rpm [Ref. 8]

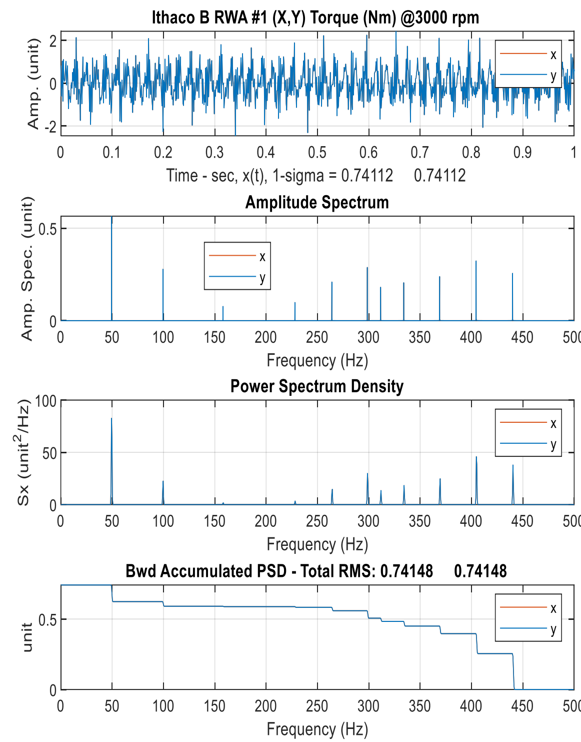


Reaction wheel - Wikipedia

RWA 3-axis Force




RWA 3-axis Torque



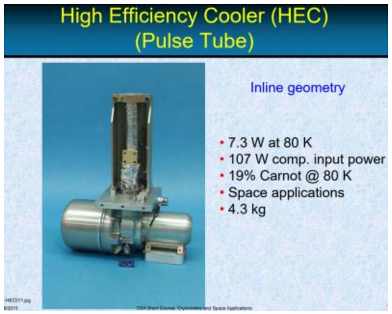

## Drive requirements

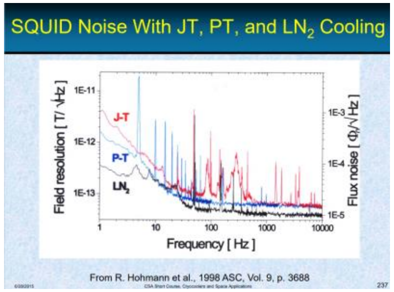
- The LOS pointing errors should be minimized to meet the jitter requirements under BUS RWA disturbance.

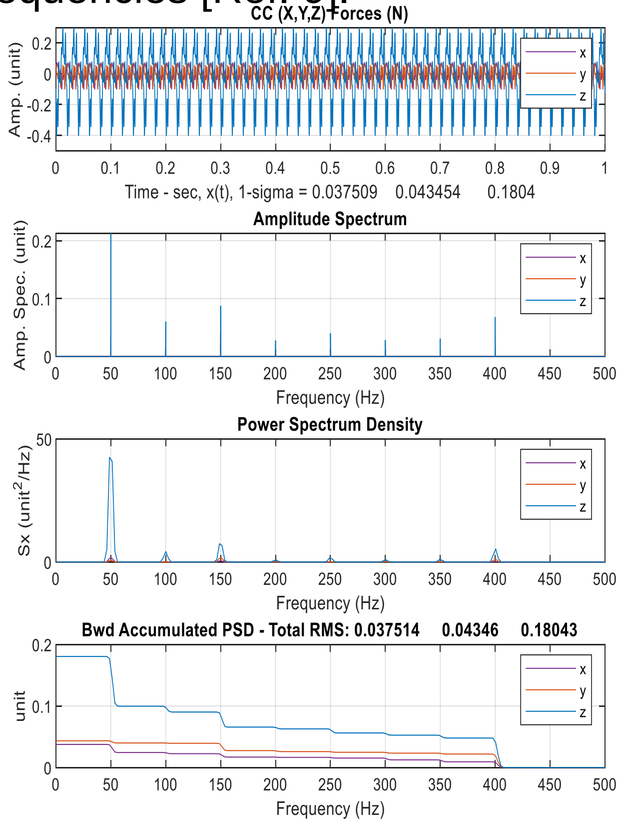
# *Payload Internal Disturbances and Drive Requirements*

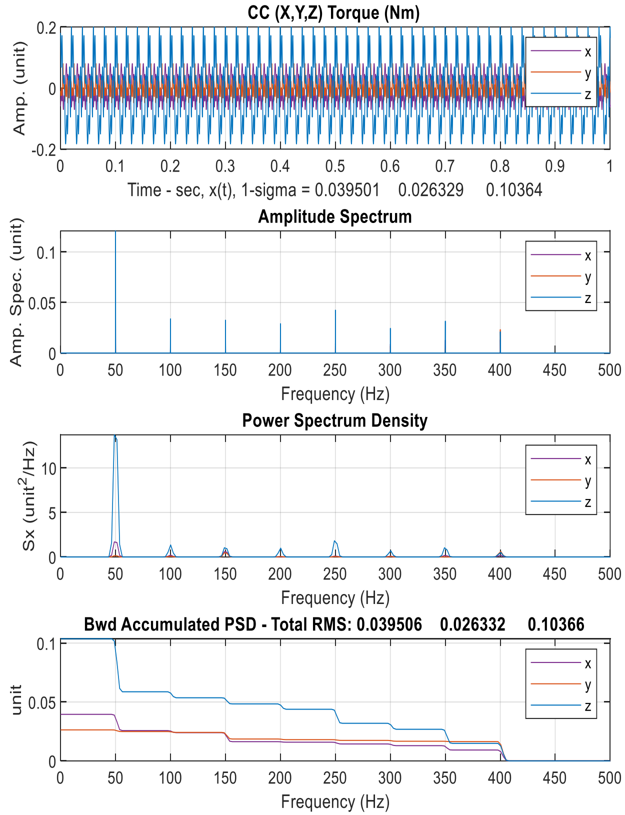
## Descriptions

- Every optical payload has cryocooler to regulate its environmental temperature. The good news is that the coolant pumping frequency can be tuned to avoid the potential payload structural resonance frequencies [Ref. 9].



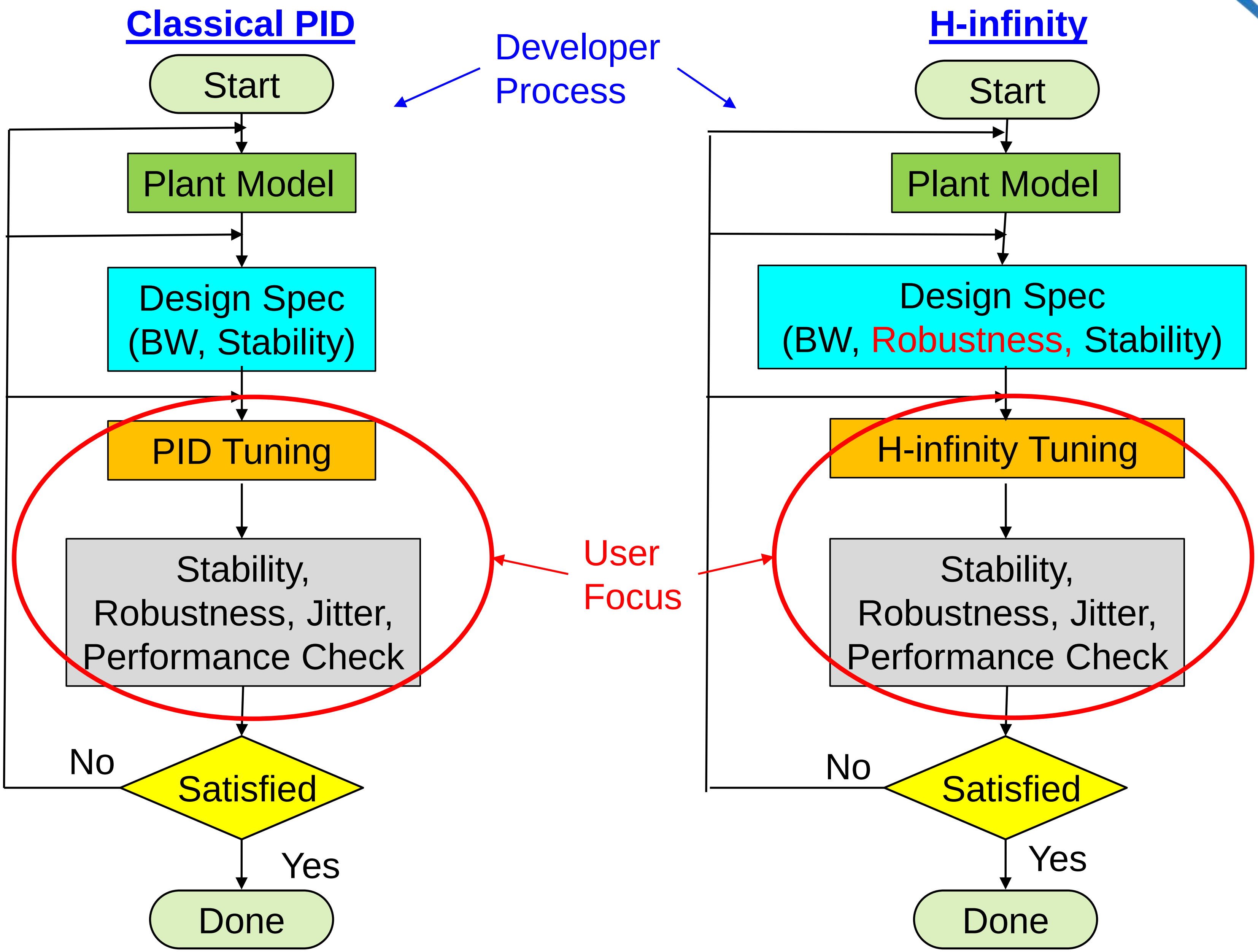




## Drive requirements

- The LOS pointing errors should be minimized to meet the jitter requirements in the presence of payload internal disturbance.

# Control Design Flow Chart



# Requirements on User Design

- Control design (Payload/BUS Controller)
  - *Stability Margins: MIMO* ***[6dB, 30deg]***
  - ***Robustness***
  - *Payload BW:* ***~200 Hz sampled @20 KHz, BUS BW: ~ 0.005~0.01 Hz sampled @10 Hz***
  - *Gimbal Az/El controller errors (command slewing only, no disturbance):* ***< 1 urad (0-p)***
- LOS Disturbance Rejection
  - *LOS-Az/El (both axes) MIMO disturbance torque reduction ratio:* ***> 200:1 (Goal: 500:1)*** *[Ref. 2,12]*
  - *LOS-Az/El (both axes) Jitter Metric (using Pittelkau standard definitions [Ref. 11])*
    - **Step-Starer with window sizes [20, 100, 200] msec**
      - *Smear* ***< 0.5 urad***
      - *Jitter* ***< 0.5 urad***
    - **Scanner with window sizes [20, 50, 100] msec**
      - *Displacement* ***< 0.5 urad***
      - *Smear* ***< 0.5 urad***
  - *All above requirements need to be met under Aerospace/NASA defined slew profiles and RWA/CC disturbances*

# *Benchmark Problem Rollout to GN&C Community*

- NESC team is currently formulating a plan to rollout this benchmark problem to the GN&C community of practice
- Seeking suitable public facing website to host benchmark problem
- Developing a set of objective user solution scoring metrics
- Plan to showcase this benchmark problem (and other related problems) at the European Space Agency (ESA) GNC Conference in June at Sopot, Poland

***Seeking GN&C Community of Practice feedback on benchmark problem rollout approach to maximize exposure and utility***

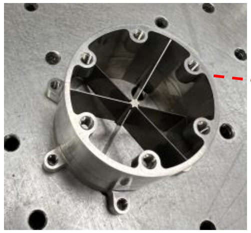
## *Potential Lab Test Follow On Using “Aerospace Optical Fast Steering Mirror Testbed”*

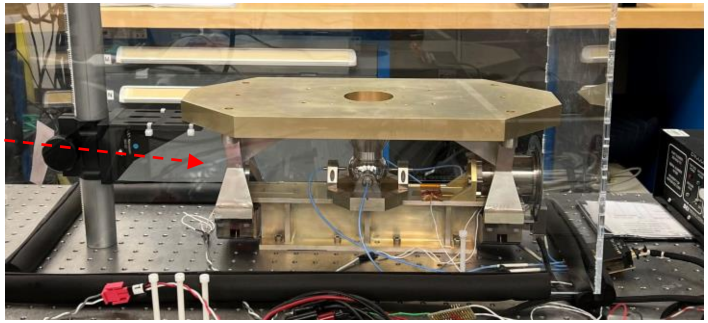
# Scope of Work

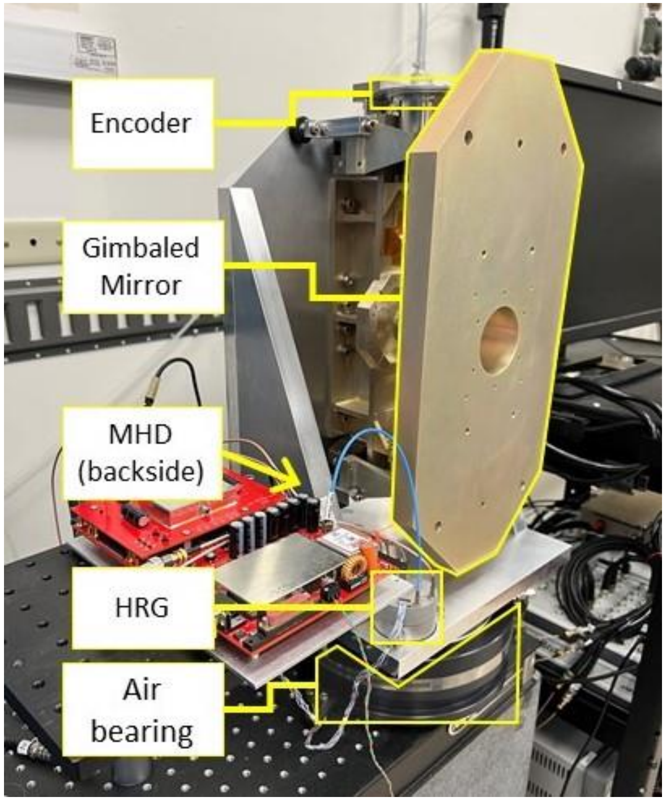
- Utilize Aerospace ***<u>Disturbance Rejection Testbed (with unknown disturbance source)</u>*** to test/evaluate users' innovative disturbance rejection algorithms
- A plant dynamics will be provided via in-house SystemID tools
- Estimated hours of implementing/testing each user algorithm: ~ 40 Hours via dSpace

## Single Axis Mirror Disturbance Rejection Testbed

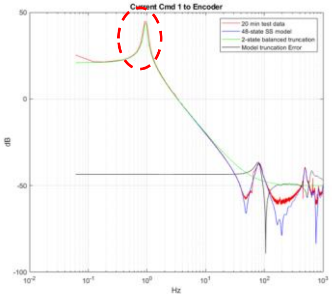
Aerospace Flexure

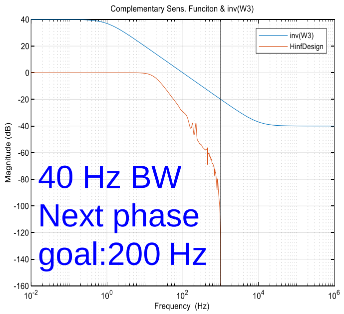


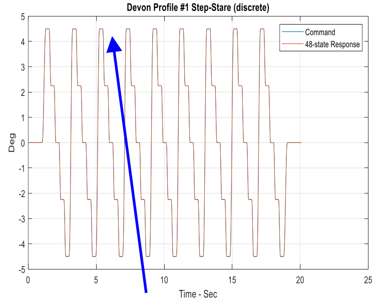





1 Hz Flexure mode




4.8 urad error

# Summary

- Benchmark observatory spacecraft will be a promising design project platform for academic and industry communities to develop innovative disturbance rejection solutions for spacecraft observatories
- Dynamic modeling, command profiles, and disturbances have been all well defined and built for industry and academic users

- Point of contact:
  - For programmatic and technical issues, please contact Cornelius Dennehy of NASA Goddard cornelius.j.dennehy@nasa.gov and Uday Shankar uday.shankar@jhuapl.edu of Johns Hopkins Applied Physics Lab.
  - For questions on dynamic models, disturbance, slew commands and Design User Guide, please contact Richard Y. Chiang, richard.y.chiang@aero.org, Richard Dolphus, richard.m.dolphus@aero.org, Michael Andonian, michael.andonian@aero.org, and Wei Huang wei.huang@aero.org of The Aerospace Corp.

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